WHERE DO PLANETS LIKE EARTH COME FROM?

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HOW DO PLANETS FORM?

Stars form and collapse out of nebula of gas and dust

↓

Proto-Planetary disk of gas and dust

↓ t=0 (CAI)

Small solid objects: "Planetesimals" (asteroid-like)

↓ t= Kyr-Myr?

Aerodynamic Drag + Gravitational Focusing = Runaway Growth

↓ t=Myr

Embryos + Planetesimals = Giant Impacts

↓ t=100s Myr

Solar System

THE SOLAR SYSTEM

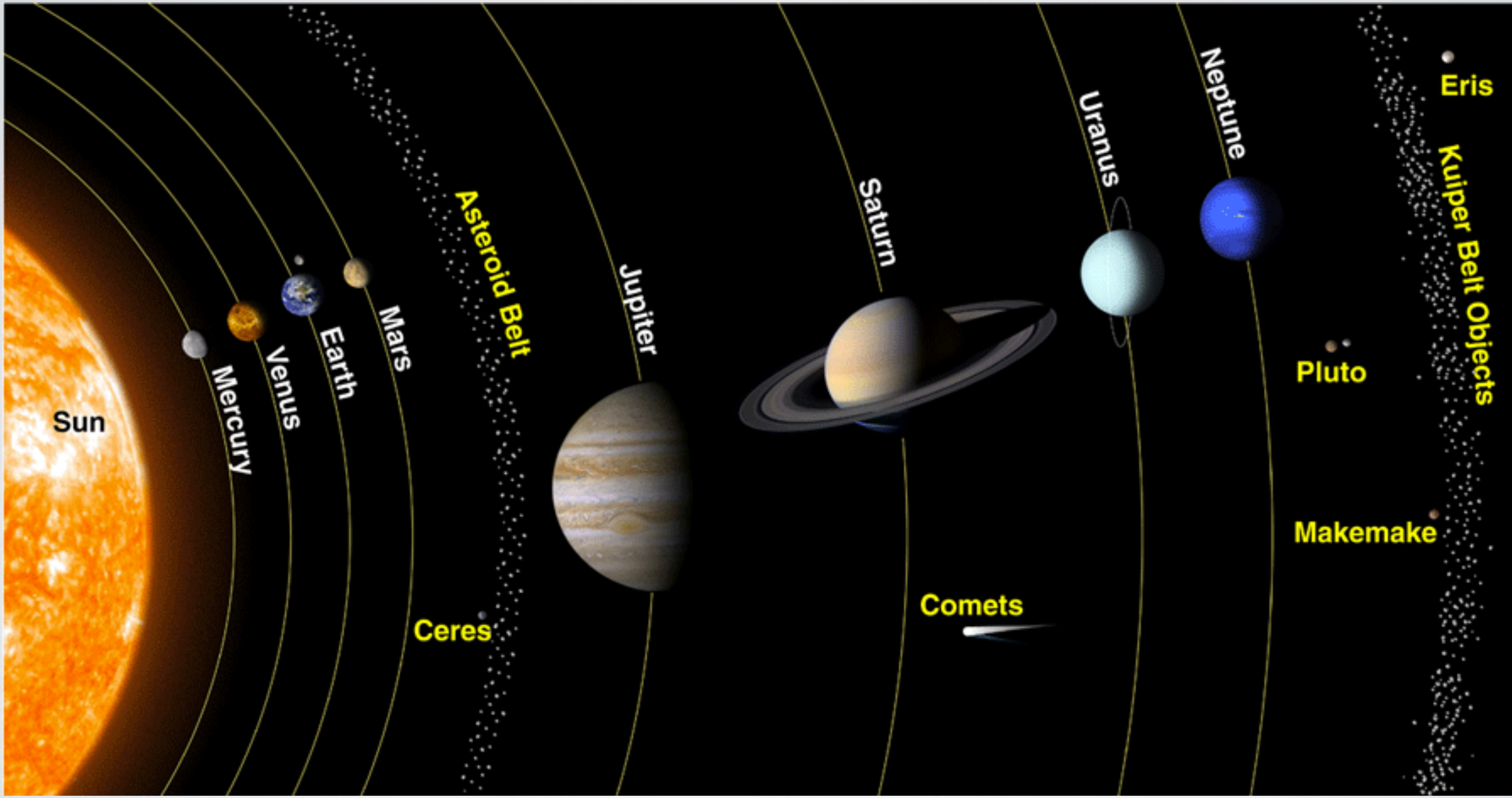
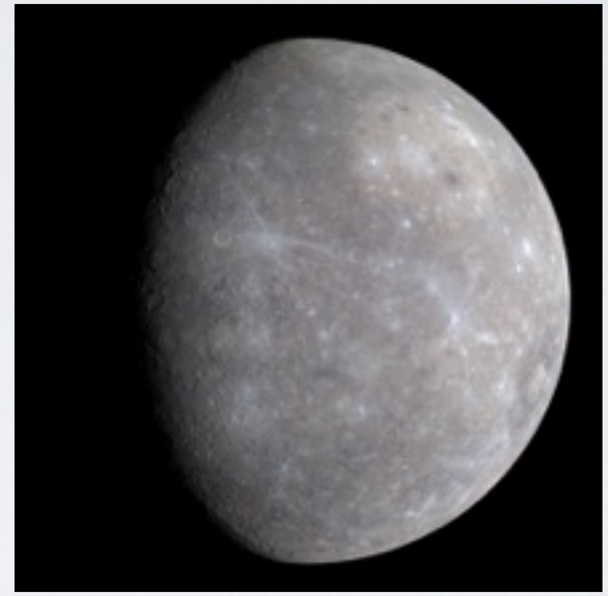
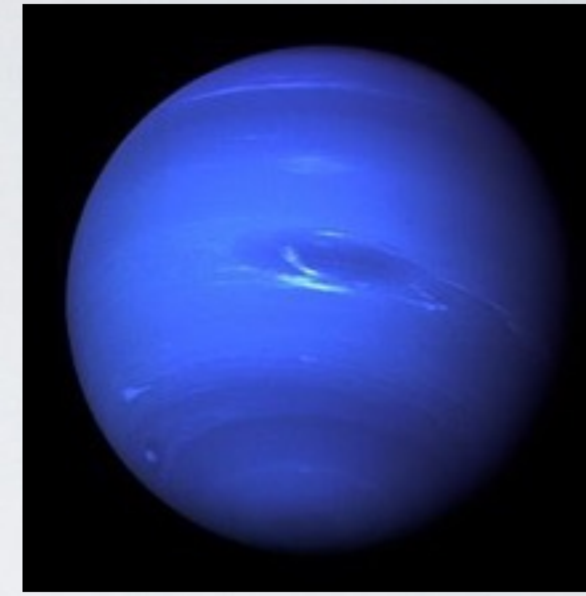
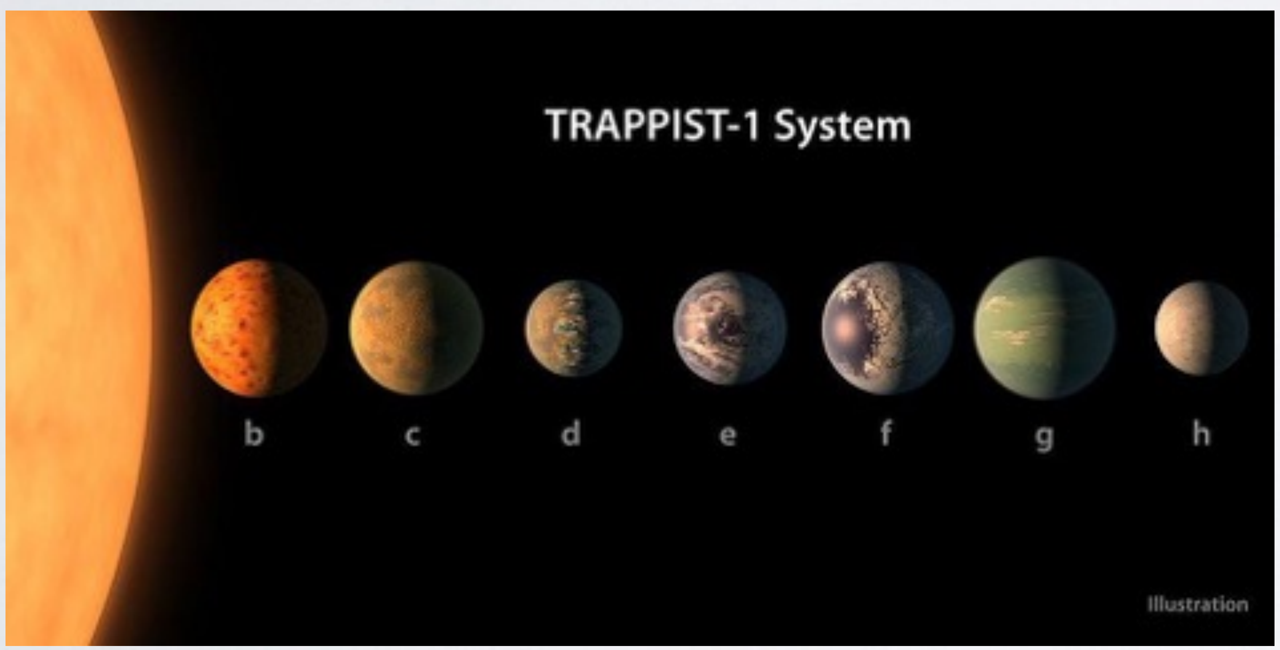


Image Credits: NASA

BUT WHY SO DIVERSE?





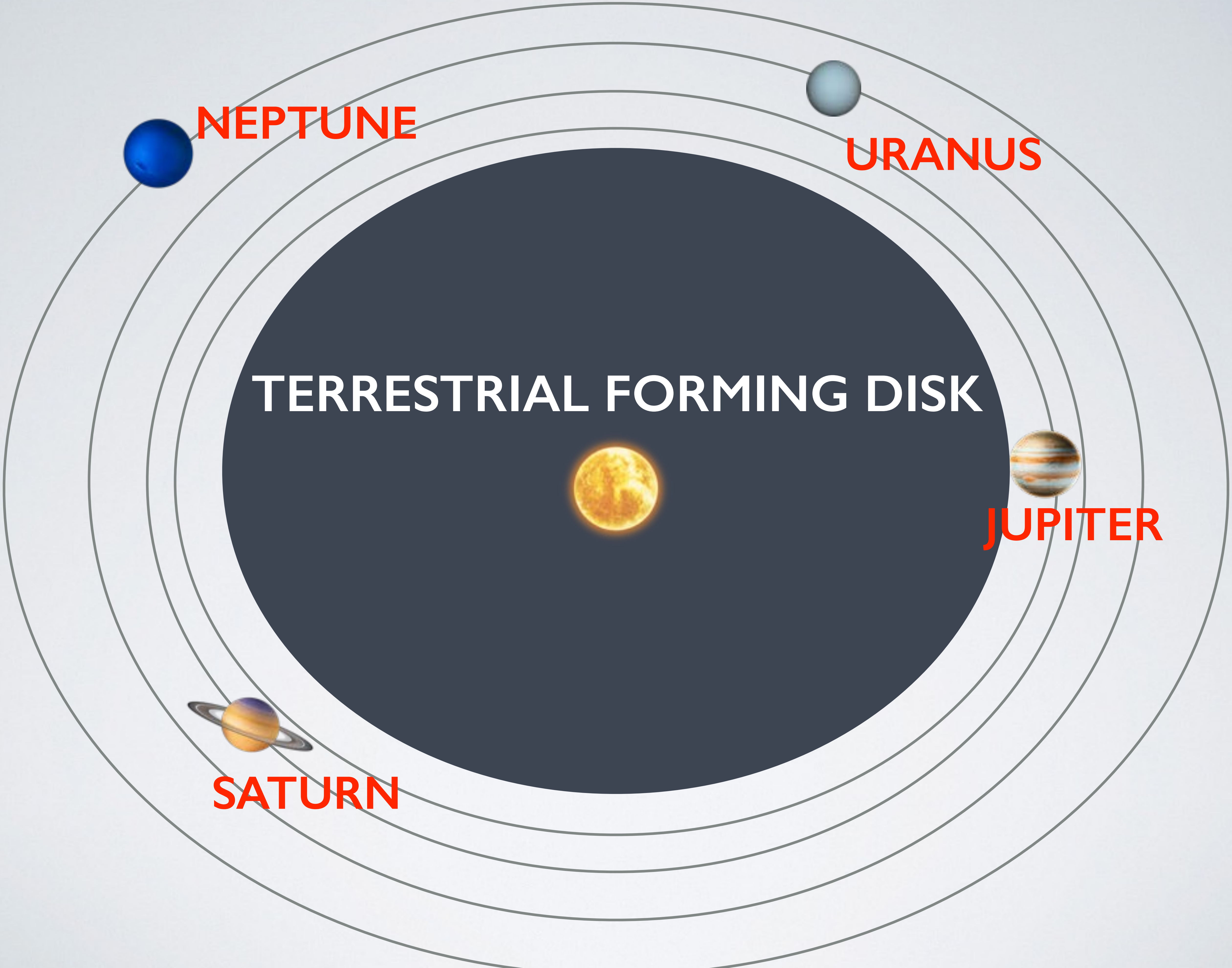


- Its complicated…..

Image Credits: NASA

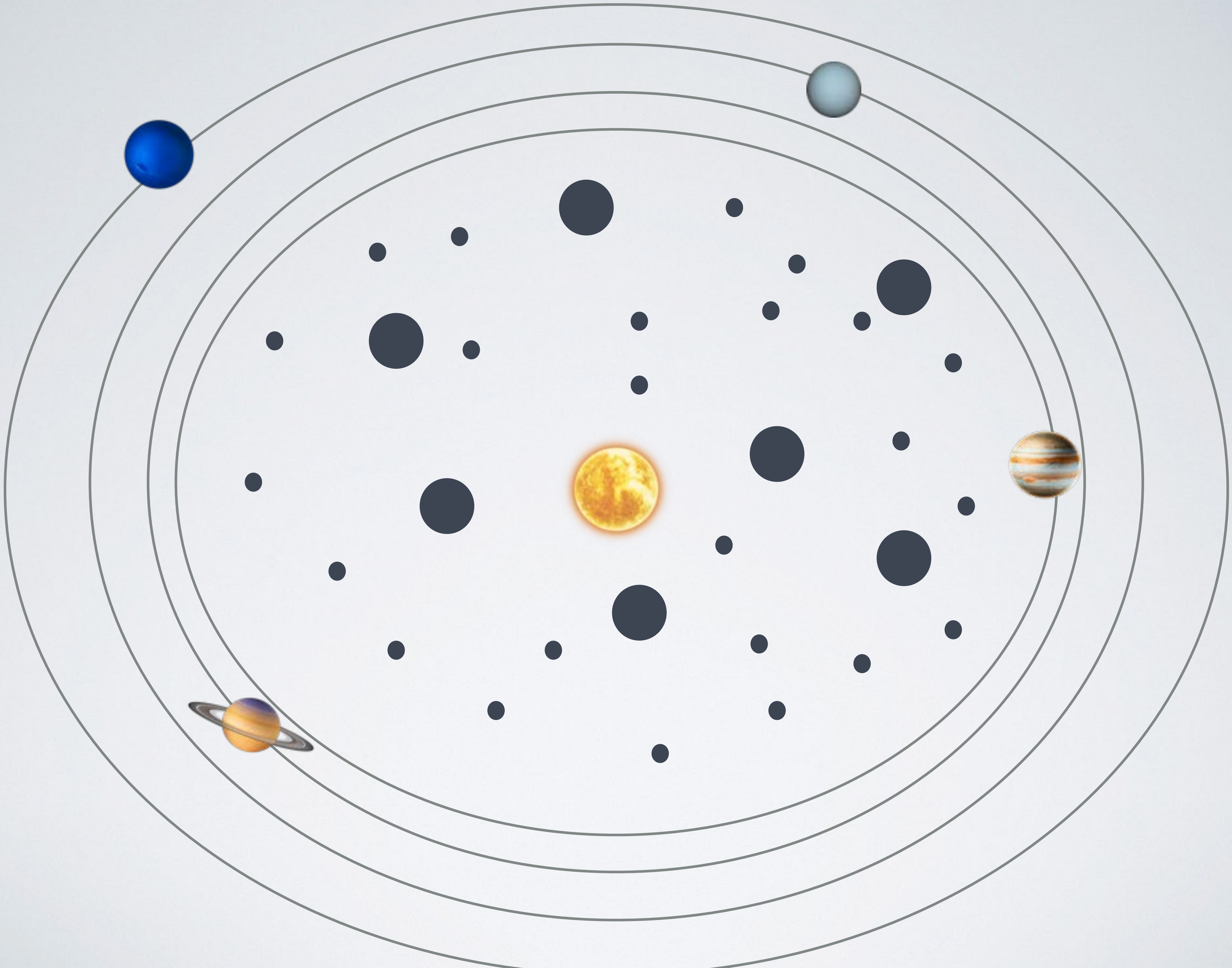
GAS GIANTS MUST FORM RAPIDLY

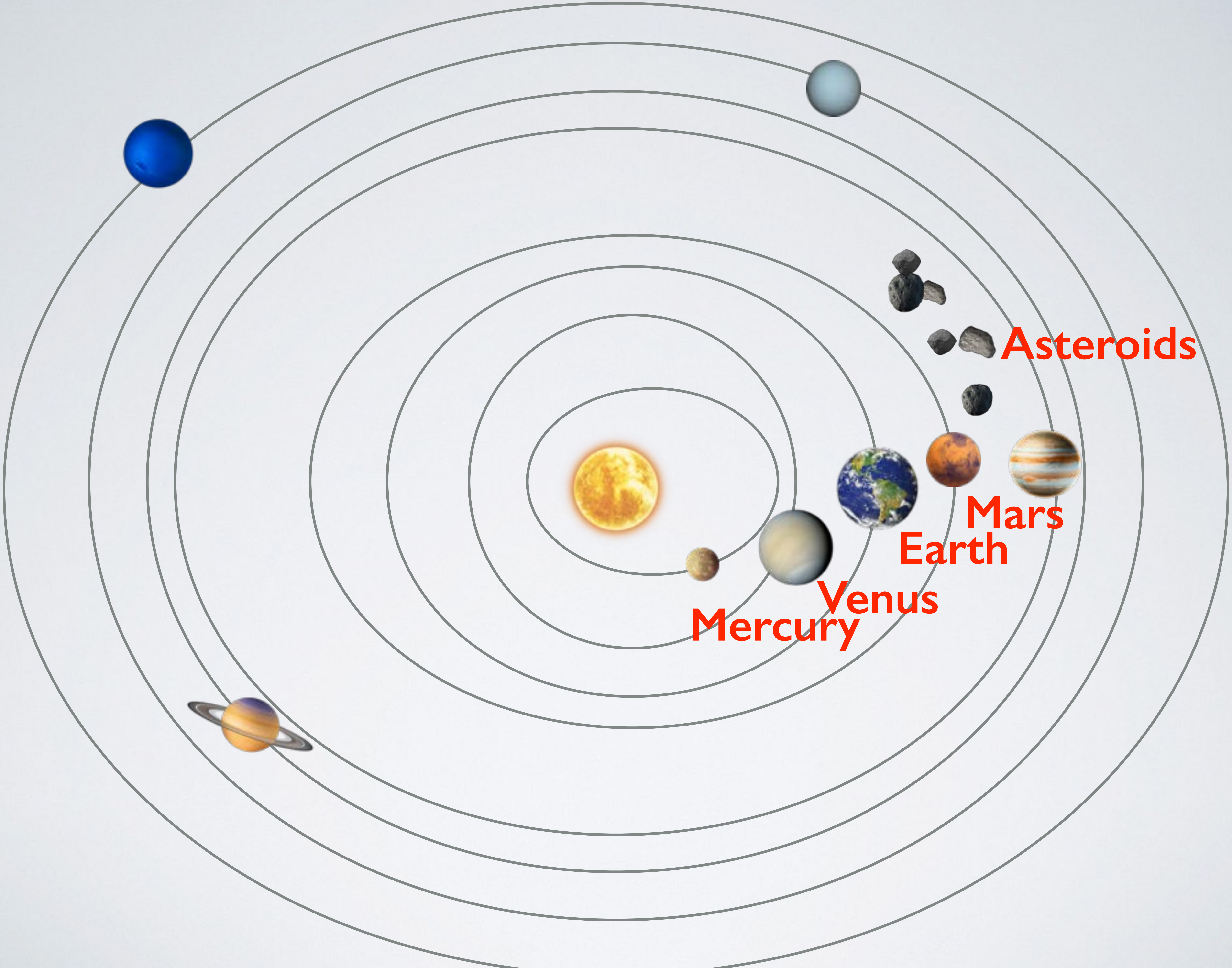
- Within a few million years, while gas is still available.
- Porto-Planetary disks only last <10 Myr (Haisch et al., 2001).
- Isotopic dating indicates it took the Earth 50-150 Myr to form (Klein et al., 2009).
- Terrestrial planets form out of the leftovers.

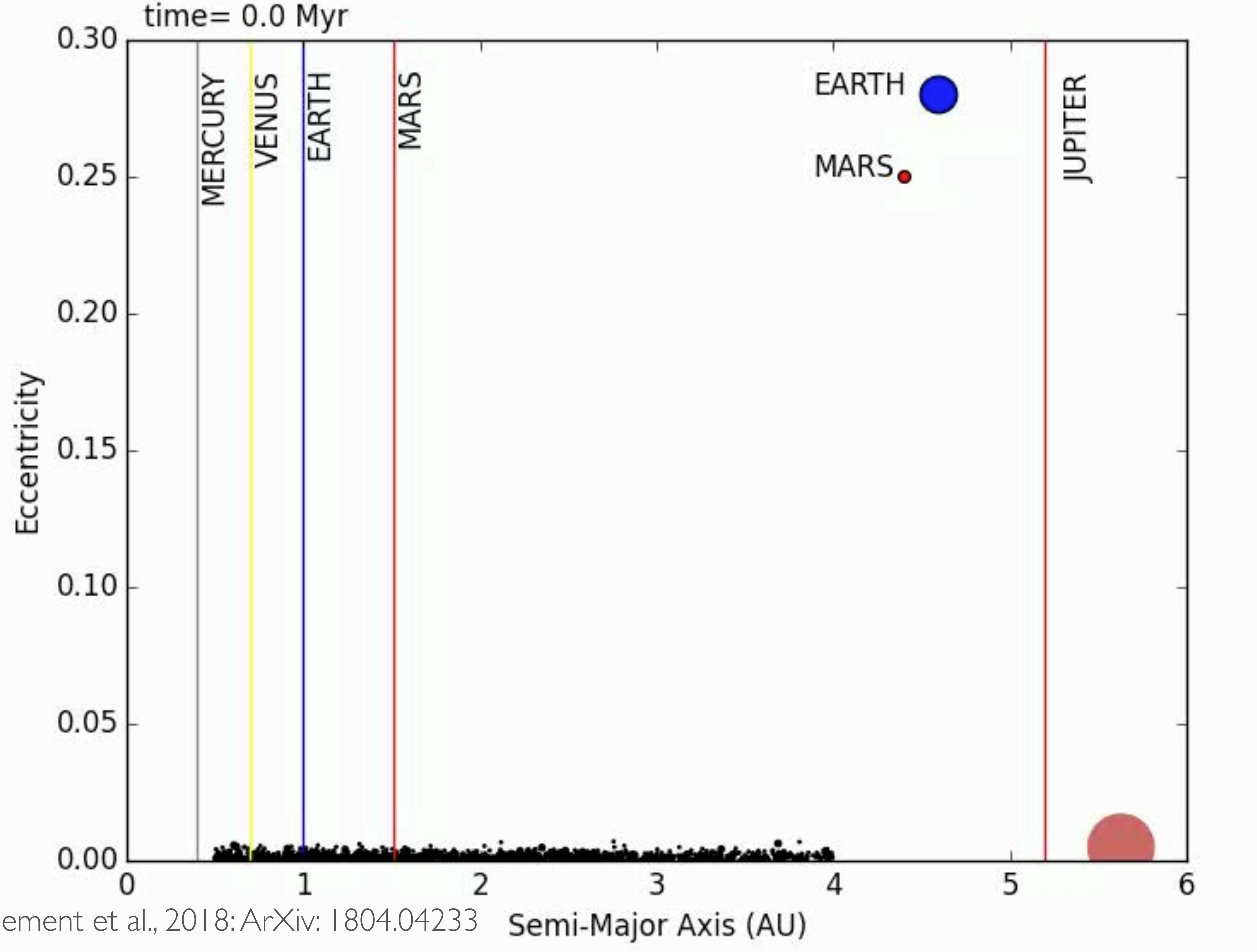

NEPTUNE
URANUS
TERRESTRIAL FORMING DISK
JUPITER
SATURN

HOW DO WE STUDY THIS NUMERICALLY?

- 1000s of equal-mass planetesimals + 100s of equal-mass planet embryos.
- Planetesimals don't interact gravitationally with each other.
- ~5 day timestep.
- 200 Myr long simulations.
- Speed up simulations by splitting Hamiltonian in to pure Keplerian component and an interaction component.




Asteroids
Mars
Earth
Venus
Mercury



Clement et al., 2018: ArXiv: 1804.04233

THESE STANDARD SIMULATIONS STRUGGLE TO:

- Produce a small Mars:
  - Mars has just 10% the mass of the Earth.

- Produce a depleted Asteroid Belt:
  - The entire belt has just a few percent of the Moon's mass.
- Replicate the low orbital inclinations and eccentricities of the actual terrestrial planets.

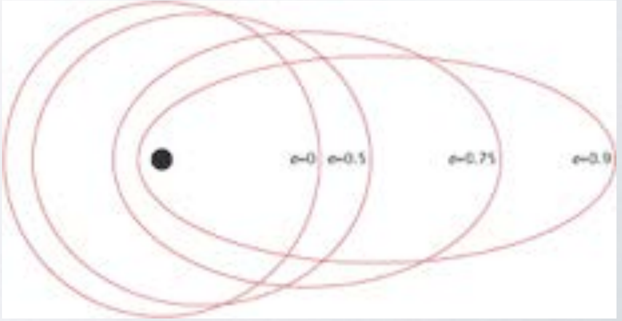
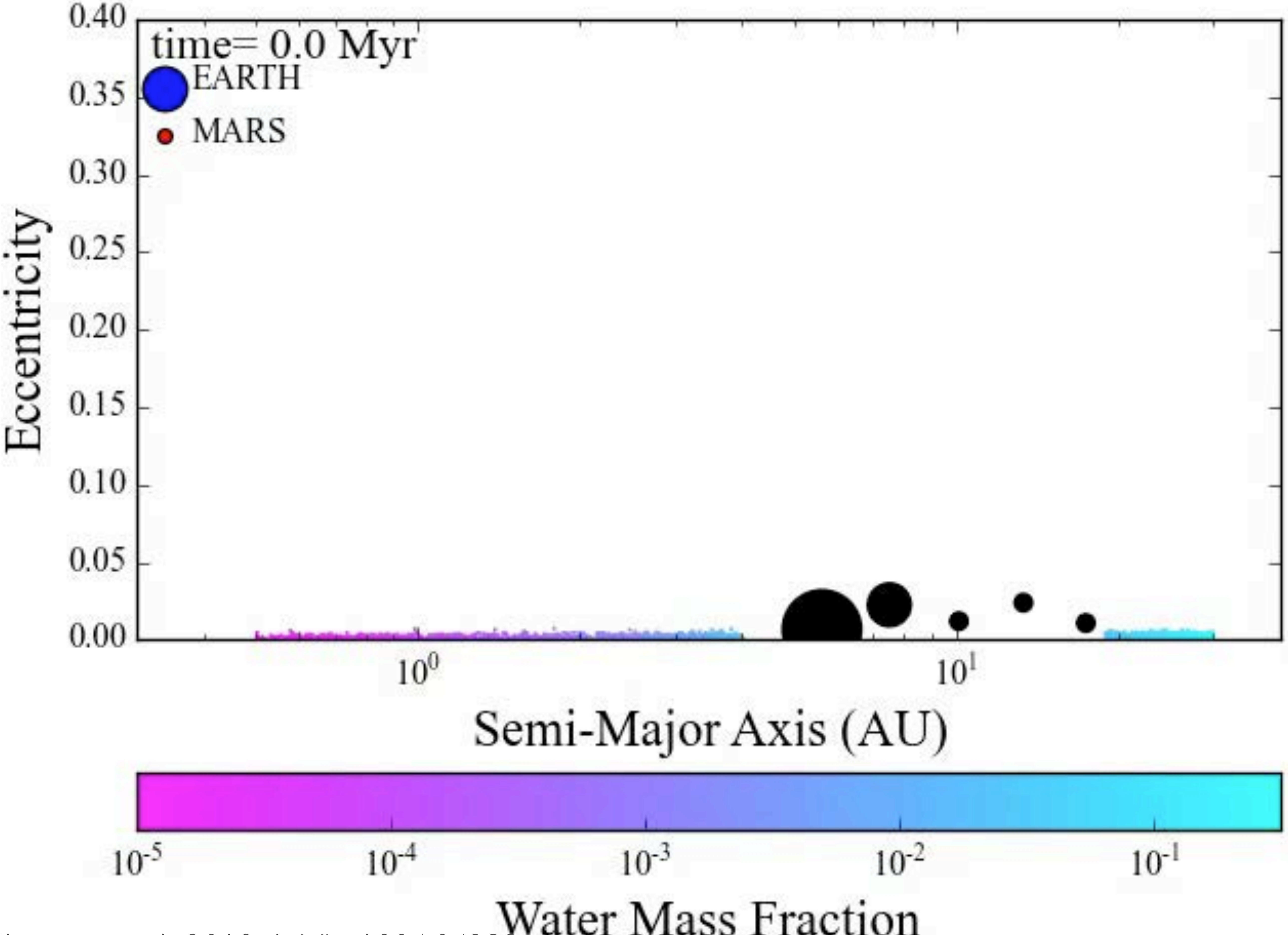


Image Credit: NASA



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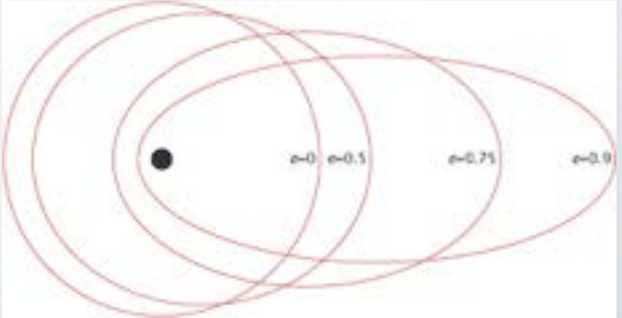

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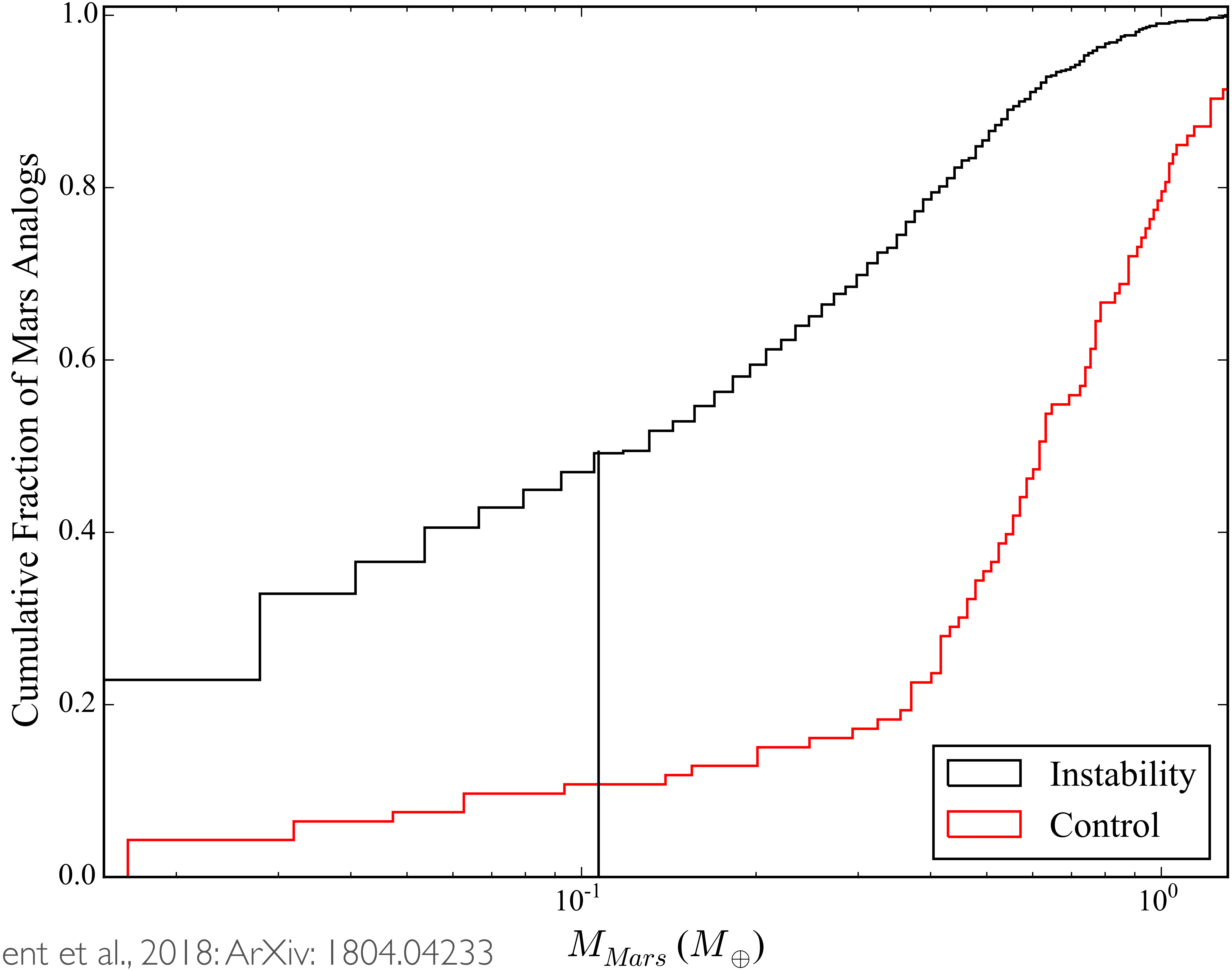

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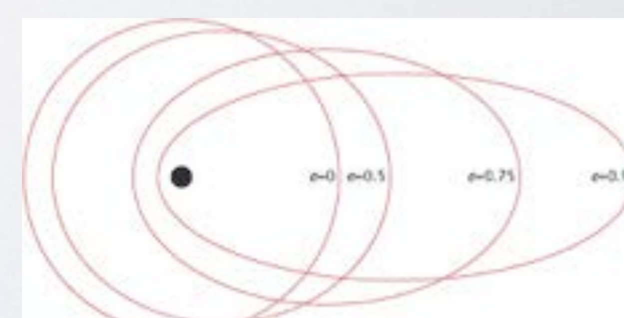

Image Credit: NASA

COLLISIONAL FRAGMENTATION

- Used Blue Waters to re-run simulations using a code which includes the effects of collisional fragmentation.
- Systems more like the solar system in terms of:
  - Eccentricities and Inclinations of planets.
  - Planet Spacing (particularly Venus-Earth spacing).
- More small bodies for longer = more dynamical friction.

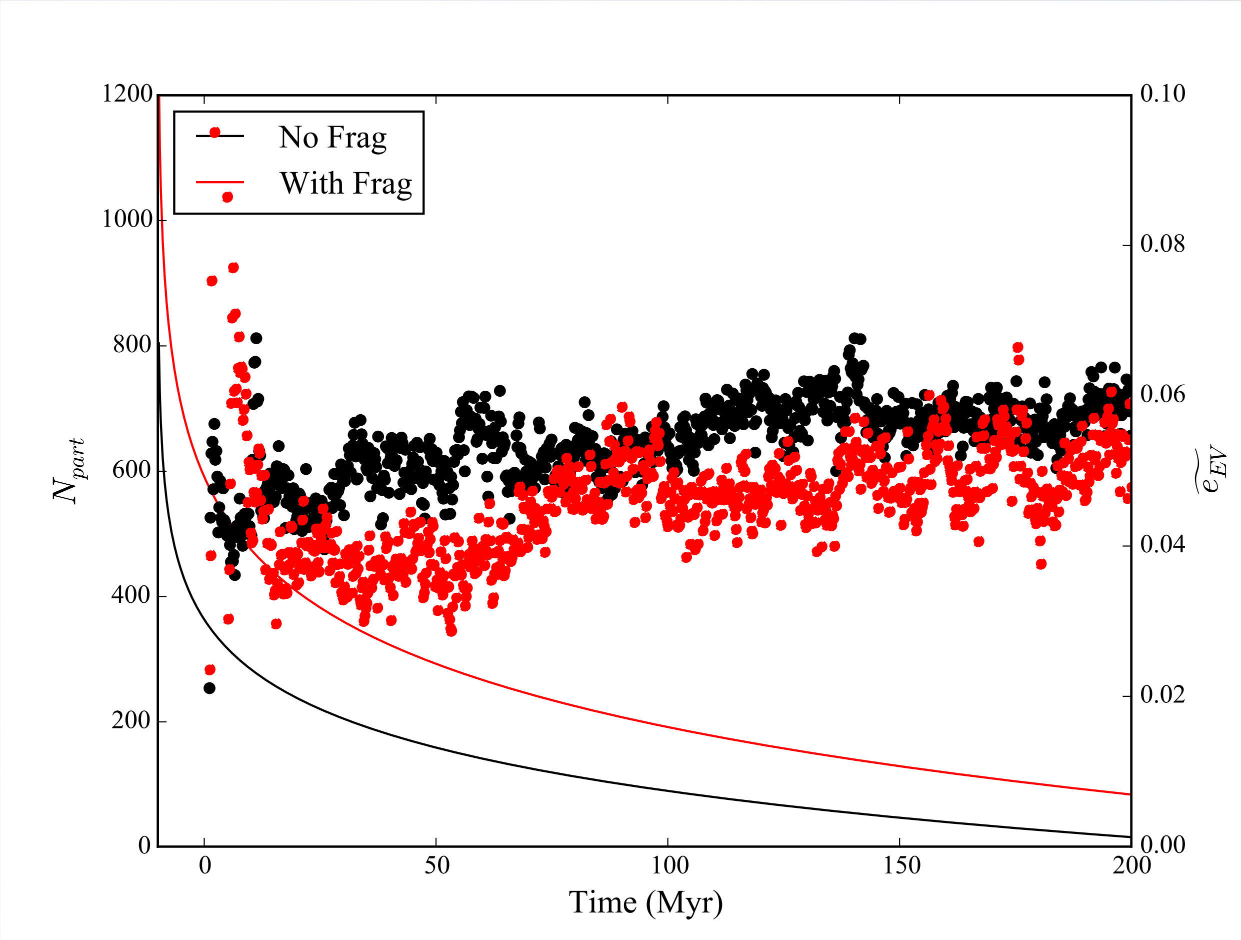

Image Credit: Clement et al., in prep

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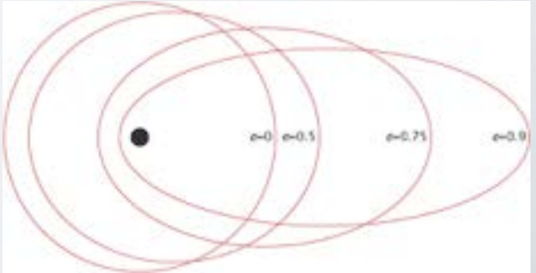


Image Credit: NASA

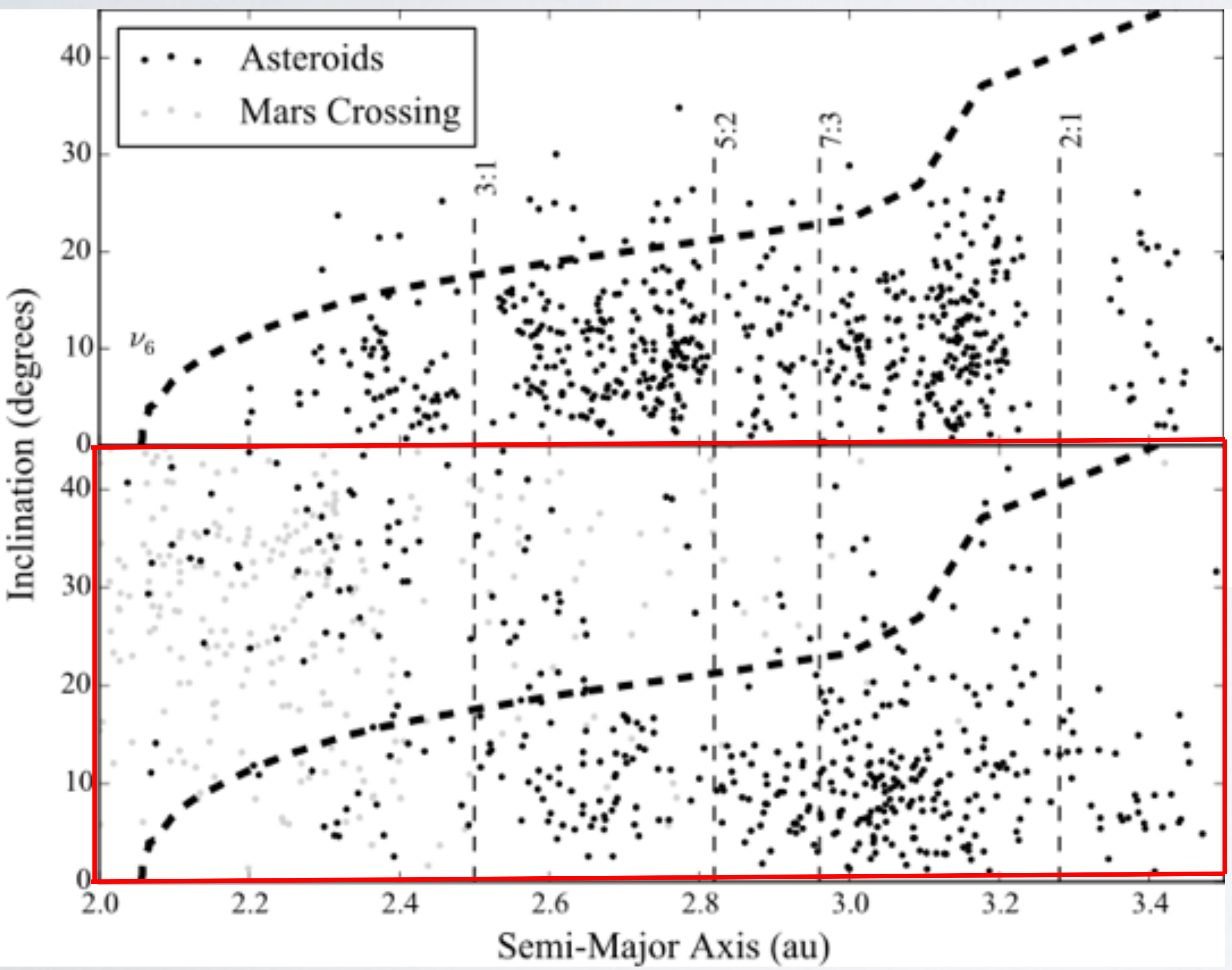
INSUFFICIENT RESOLUTION TO STUDY THE BELT

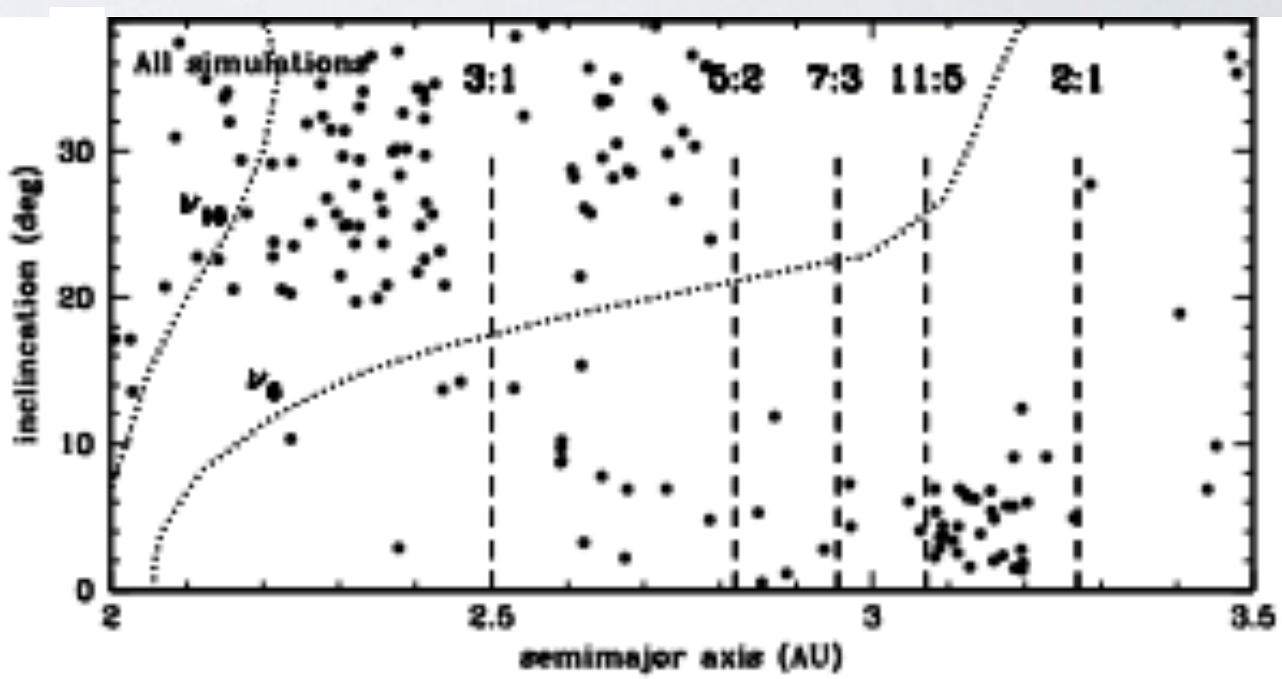
- Used a GPU code on Blue Waters:
  - 3000 Ceres-sized asteroids.
  - Fully self-gravitating.
- Good match to the actual asteroid belt's orbital structure and total mass.

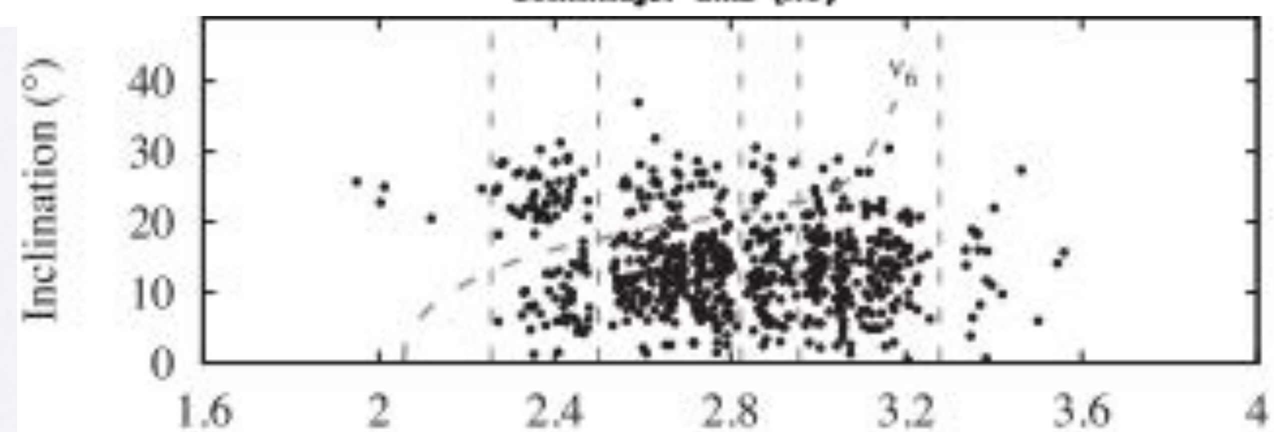
INCLINATION DISTRIBUTION

ACTUAL

Walsh & Morbidelli, 2011







BLUE WATERS Simulations

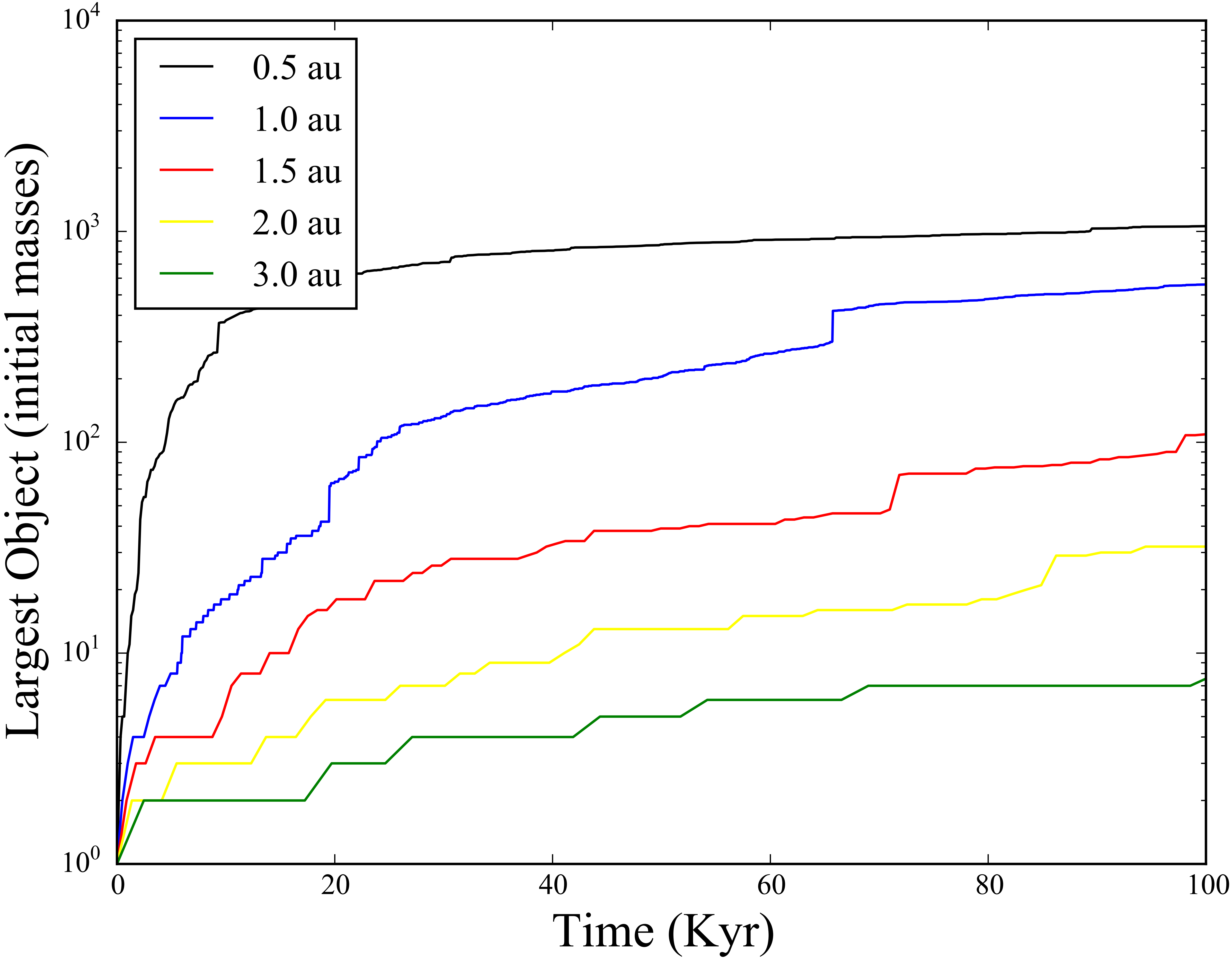
Deienno et al., 2016

HOW REALISTIC ARE THE INITIAL CONDITIONS REALLY?

- It is difficult to reproduce the masses of Mars and the asteroid belt in any model:
  - 10s of planet embryos initially in the region.
  - ~1/4 Mars mass.
  - ~160x the total present mass of the belt.

GROWING EMBRYOS WITH GPUS

- Standard initial conditions derived from narrow annulus simulations (Kokuba & Ida, 1995,1998):
  - Un-realistic Collisions.
  - 3000 x Small Moon- Asteroid sized particles.
  - Analytical conversations to other initial semi-major axes.
- Our new simulations:
  - Fully model all collisions.
  - 5000 x particles.
  - Test multiple semi-major axes.
  - Include edge effects (one in one out).
  - Include gas effects.


0.5 au
1.0 au
1.5 au
2.0 au
3.0 au
Largest Object (initial masses)
10^4
10^3
10^2
10^1
10^0
0
20
40
60
80
100
Time (Kyr)

WHY BLUE WATERS

- GPU acceleration.
- Large demand of project.
- Fellowship $$$.
- Helpful NCSA staff: special thanks to Roland Haas.

CONCLUSIONS

- An orbital instability between the giant planets can explain Mars' small mass.
- Accounting for collisional fragmentation provides a better match to the orbital excitation in the inner solar system.
- The building blocks for Mars and the Asteroid Belt were likely much smaller than for Earth and Venus.

Questions?